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Preliminary Analysis of Asynchronous Transfer Mode (ATM) over Microwave Channels

CHRISTOPHER C. YU

Advanced Systems Technology Branch
Naval Center For Space Technology

Decmeber 15, 1993

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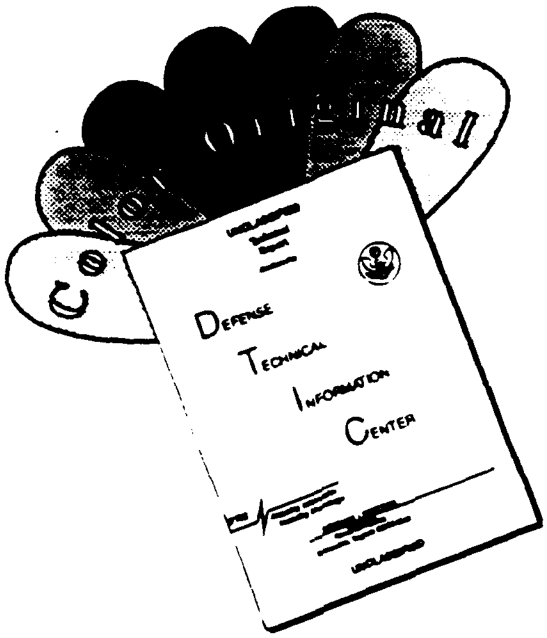

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Performance of ATM protocol over radio frequency is discussed. Preliminary analysis for various scenarios is presented. The advantages of ATM for microwave communication as well as the challenges are outlined. A simulation of modeling software package, Ptolemy, is demonstrated.

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CONTENTS

PRELIMINARY ANALYSIS OF ASYNCHRONOUS TRANSFER MODE (ATM) NETWORKS OVER MICROWAVE CHANNELS

I. Introduction

Asynchronous Transfer Mode is being hailed as the future enabling technology for a wide range of advanced high-speed data communications applications. ATM characteristics include "bandwidth on demand", and a common protocol to facilitate multi-media integration. For the most part, ATM is being developed in conjunction with SONET (Synchronous Optical NeTwork), where optical fiber is the physical medium. In many communication applications, however, fiber is not an option. Examples of such applications include transmission to satellite, airplane, and cellular communications. This paper addresses some of the preliminary issues and considerations of maintaining the ATM protocol "off the fiber", and over radio frequency.

By communicating over radio frequency versus optical fiber, a higher bit-error rate is typical, as well as a different distribution of these errors. An ATM cell is defined to be 53-bytes, 5 bytes of header information and 48 bytes of data payload [1]. Bit-errors of header information of an ATM cell will cause a packet loss. The current ATM protocol provides for 1 byte of Header Error Control (HEC) to mitigate header errors. The ATM protocol also provides various modes of transmission reliability. A tradeoff between guaranteed service and transmission rate is incurred. The performance of these ATM-related issues for transmission over microwave channels will be discussed.

A simulation framework is essential for the study of ATM issues as the system modeling is refined and extended. Within the past five years, numerous graphical-based software applications have emerged for system simulation and modeling. These software packages range the spectrum of the design process -- from high-level networking simulation, to DSP functional analysis, to low-level code-generation. As part of the preliminary analysis completed in this report, one example of these software packages, Ptolemy, is demonstrated.

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II. Microwave Channels

Optical fiber provides high bandwidth transmission, low attenuation, and immunity from external interference. It is clearly the physical medium of choice for digital communications, and is rapidly replacing existing coaxial cables [2]. The bit-error rate for optical fiber is dependent on material attenuation. Regenerative repeaters are used throughout the fiber cable to effectively solve the attenuation problem. Typical bit-error rates for existing optical fiber installations is on the order of 1E-12.

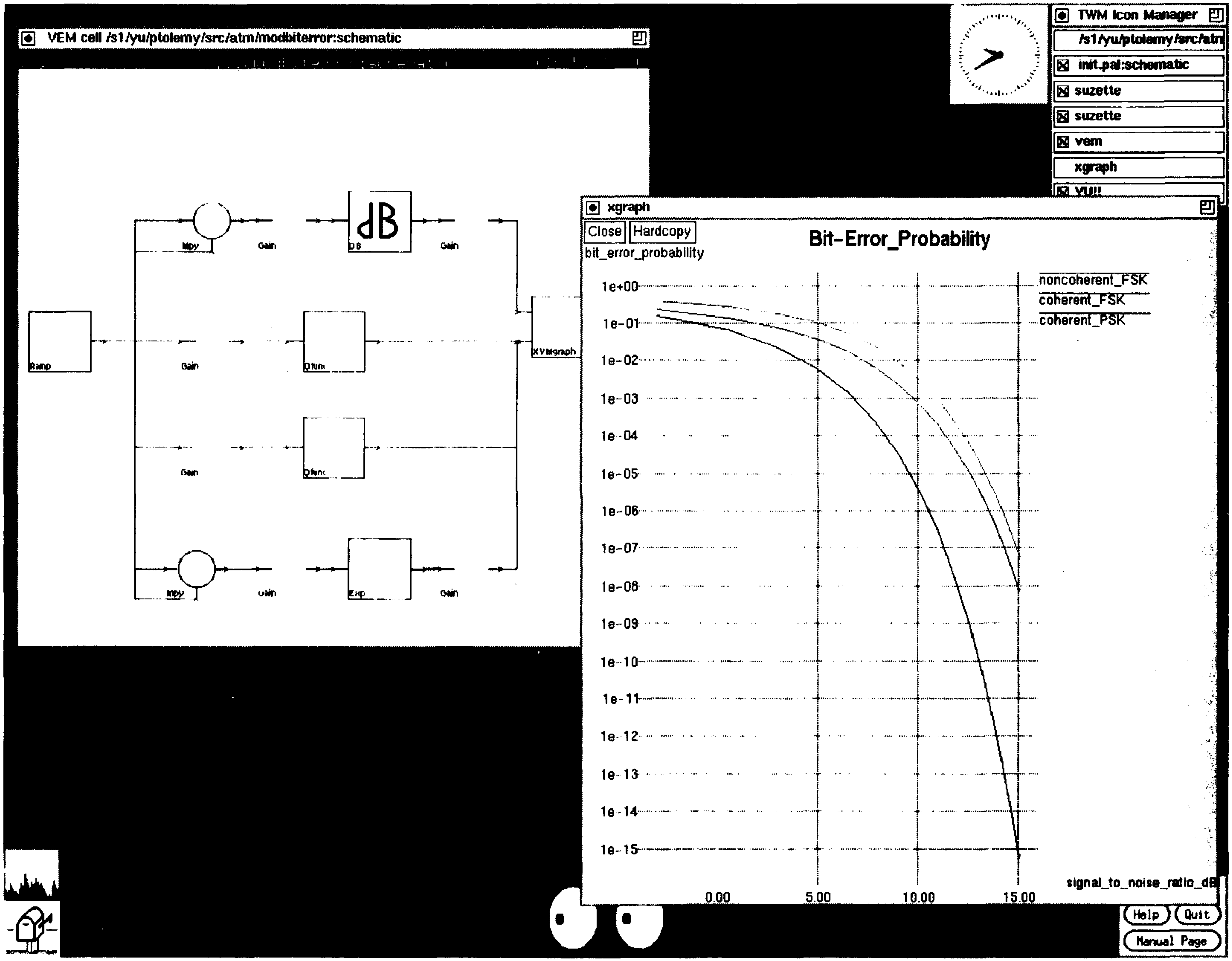
Performance of Radio Frequency (RF) communication is a function of the signal power available and the noise characteristics of the channel. For digital communication, the probability of bit-error is also dependent on the choice of modulation. For example, for binary phase-shift keying (BPSK), the probability of bit-error, P_e, can be determined for a signal amplitude of A volts and Gaussian noise with zero mean and variance σ^2:

$$P_e = \frac{1}{2} \int_{\frac{A}{2}}^{\infty} f_0(v)dv + \frac{1}{2} \int_{-\infty}^{\frac{A}{2}} f_1(v)dv$$

where $f_0(v)$ is the probability density of no signal transmitted, and $f_1(v)$ is the density of signal of amplitude A being transmitted. Upon simple manipulation, we can determine P_e in terms of the unit Gaussian Φ:

$$P_e = 1 - \Phi\left(\frac{A}{2\sigma} \right)$$

In figure 1, the probability of bit error as a function of the Signal-to-Noise ratio of a communication channel for various modulation schemes is plotted [3]. (Note: Figures include a graphical description of the analytical function used to generate the plots. The figures are actual screen images of a software application, Ptolemy, displayed on an X-Windows monitor. This design environment, Ptolemy, will be further described in Section VII. For now, only the plots are referenced.)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Manual Page

III. ATM Protocol

ATM is a part of the overall B-ISDN (Broadband Integrated Services Digital Network) definition, which is based on the existing ISDN standard [4]. ISDN, in turn, is a specification, developed by CCITT (International Telegraph and Telephone Consultative Committee), intended to define a standard interface for telecommunications. By conforming to a defined model, all ISDN-compatible equipment (e.g., telephones, computer terminals, personal computers) will be able to attach to a network and connect to any other attached system.

Work on the formation of ISDN can be traced as far back as 1976. In the late 1980's, CCITT anticipated that future networks will require the ability to provide for high bit-rate services. Several key technology developments motivated this decision, including: 1) the development of optical fiber transmission systems that offer low-cost, high data-rate channels, and 2) microelectronic circuits that can offer high-speed, low-cost switching devices. CCITT decided to create an ISDN related, but separate definition, namely B-ISDN.

For B-ISDN, the transfer mechanism of information across the user-network interface is defined to be ATM. Two layers of the B-ISDN protocol architecture relate to ATM functions. These layers include one that provides the actual packet transfer capabilities, and an ATM adaptation layer (AAL), which is service independent. The AAL maps higher-layer information into ATM cells to be transported over B-ISDN. At the destination end, information is collected from ATM cells for delivery to higher layers.

The ATM cell is defined to be 53 bytes, 5 bytes of which is the header. The fields of the header are as follows:

GFC - generic flow control field
VPI -virtual path identifier
VCI - virtual circuit identifier
PT - payload type
CLP - cell loss priority
HEC - header error control

The format of the ATM cell is provided in Appendix A.1.

IV. Detection/Correction Mode

The ATM header includes a one byte field, HEC, Header Error Correction. The HEC is implemented as a cyclic redundancy check type of error-detecting code. Essentially, the HEC can correct for 1 bit errors in the header, and can detect 2 bit-errors but cannot correct. The current ATM protocol definition also defines a state diagram to handle burst errors (see Appendix A.2). If no errors occur as ATM cells arrive, the receiver stays in error-correction mode. When an error is detected or corrected, the receiver enters detection mode. Any subsequent errors in ATM cell is treated as a corrupted address. That is, even if it is a 1-bit error, and theoretically can be corrected, it is assumed to be corrupted. This error handling process is intended to detect burst noise.

The state-diagram to handle burst noise, can be modeled as a 3-state Markov chain. State I represents the system being in "Correction Mode". State II represents the system after a single bit-error in the Header that has been corrected and is passed as a valid cell. State III denotes the system after multiple bit-errors have been detected that cannot be corrected, and the cell is discarded. We define the following probability transition parameters:

α = probability of 0 bit-error in header
β = probability of 1 bit-error in header
γ = probability of 2 or more bit-errors in header

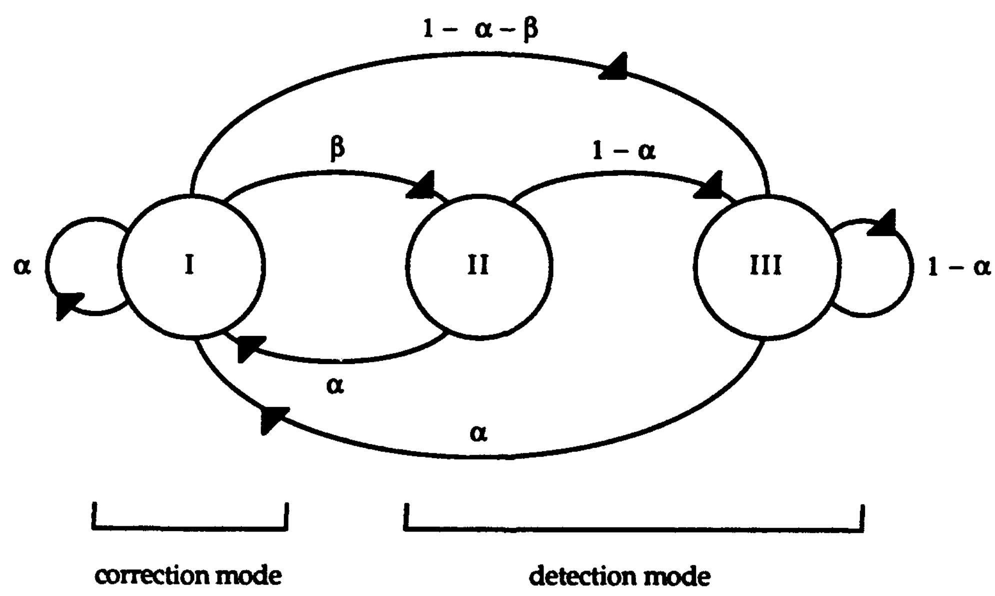


Figure 2

Each bit transmission can be modeled as a Bernoulli trial with a "success" corresponding to a bit error. This, of course, is simply a binomial distribution of bit errors. We define the probability of bit-error to be "p". Since there are 8 bits per byte, and 5 bytes per header, we have 40 bits per header. Therefore,

$$\alpha = \binom{40}{0} p^0 (1-p)^{40}$$
$$\beta = \binom{39}{1} p^1 (1-p)^{39}$$
$$\gamma = 1 - \alpha - \beta$$

The Markov transition probability matrix P:

$$P = \begin{vmatrix} \alpha & \beta & 1-\alpha-\beta \\ \alpha & 0 & 1-\alpha \\ \alpha & 0 & 1-\alpha \end{vmatrix}$$

The steady-state probability equations for Π_1, Π_2 and Π_3 (where Π_i is the steady-state probability for state "i")

$$\Pi_1 = \alpha \Pi_1 + \alpha \Pi_2 + \alpha \Pi_3$$
$$\Pi_2 = \beta \Pi_1$$
$$\Pi_3 = (1 - \alpha - \beta)\Pi_1 + (1 - \alpha)\Pi_2 + (1 - \alpha)\Pi_3$$
$$1 = \Pi_1 + \Pi_2 + \Pi_3$$

Evaluating:

$$\Pi_1 = \alpha$$
$$\Pi_2 = \alpha \beta$$
$$\Pi_3 = 1 - \alpha - \alpha \beta$$

The steady-state probability of the system being in correction mode or being in detection mode can be determined.

$$\Pr(\text{correction mode}) = \Pi_1 = \alpha$$
$$\Pr(\text{detection mode}) = \Pi_1 + \Pi_2 = 1 - \alpha$$

The probability of the system recognizing a valid cell is state I and state II.

$$\Pr(\text{valid cell}) = \Pi_1 + \Pi_2 = \alpha + \alpha\,\beta = \alpha(1 + \beta)$$

$$\Pr(\text{discarded cell}) = \Pi_3 = 1 - \alpha - \alpha\,\beta$$

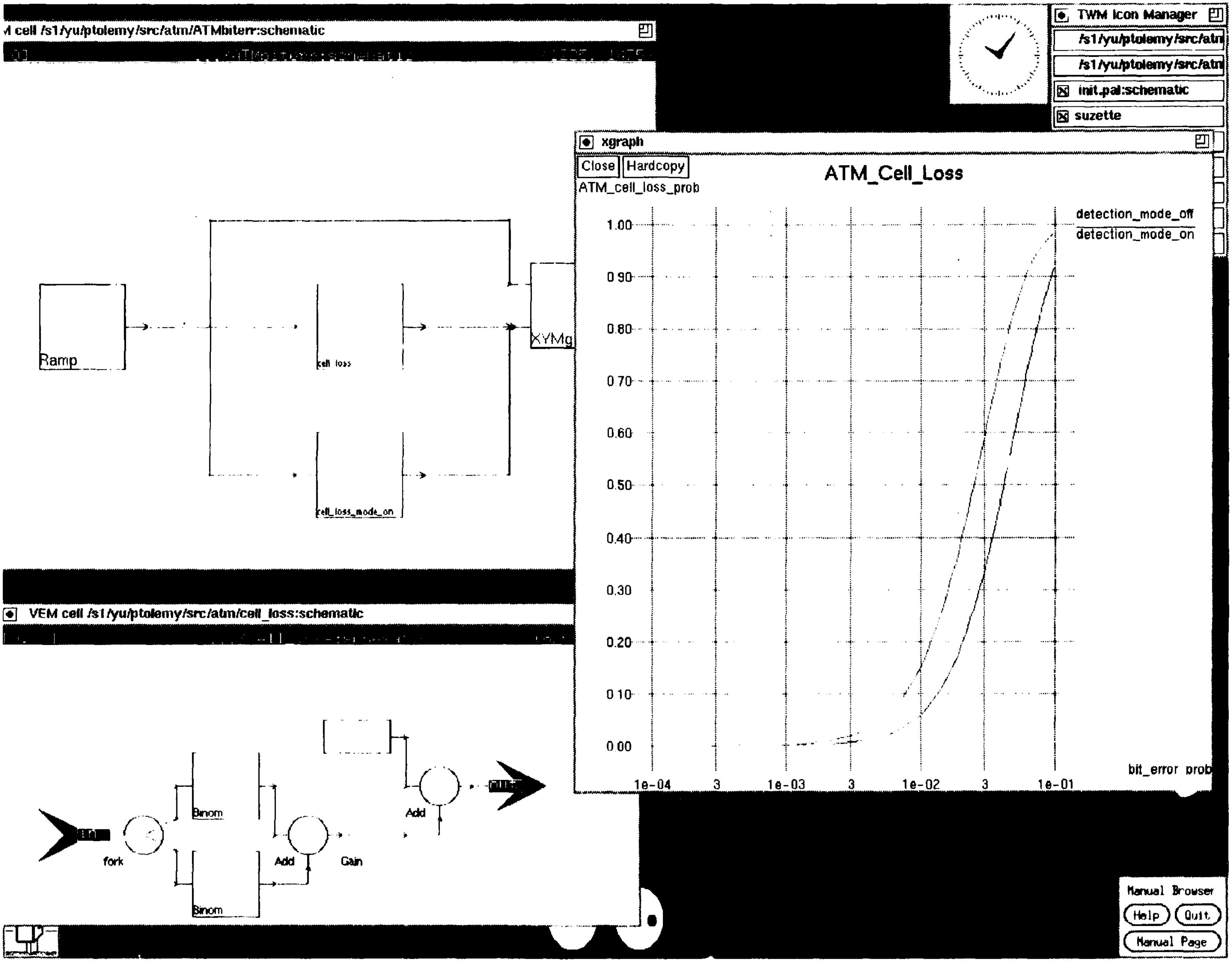
When a header has been corrupted, the entire cell is discarded, including the 48-bytes of data payload. Probability of ATM packet loss is plotted as a function of bit-error probability in Figure 3, for the cases of detection mode "on" and "off" (detection mode "off" denotes that the system is set to always correct for 1 bit-errors). There is the probability that the header will be altered to a valid address, in which case the data is not discarded, but rather sent to the wrong destination. For this to occur, a header must not only be corrupted to a valid address, but it must be altered to an "active" address as well. The probability of this event occurring is considered to be negligible [5].

V. ATM issues

A cell loss in an ATM network can occur in two ways: 1) bit errors to corrupt the header, and 2) overflow of switch buffers. Because ATM is being developed with SONET, corruption of header due to bit-errors are considered negligible. Most of the current research effort in ATM has been concentrated on the problem of network congestion management and preventing buffer overflow. The ATM protocol has one bit of the control header that can be used to define a cell to be high or low priority. In the case of increased network congestion, it is anticipated that this priority bit can be used to ensure certain cells not to be dropped by the network.

A number of different buffer policies have been proposed for ATM networks. A straight-forward buffer access discipline is first-come-first-served (FCFS), where if an input cell arrives at a full queue, it is discarded. Another buffer policy is FCFS with pushout [6]. It is similar to FCFS, but if a high priority cell arrives, it will push out a cell of low priority that is in the queue. FCFS with pushout provides improved reliability of high priority cells not to be discarded. The tradeoff is that FCFS with pushout is more complex to implement. FCFS and FCFS with pushout are just two example buffer disciplines.

Besides buffer policy strategies, a second area of research activity is network bandwidth management. The extent of the dynamic bandwidth concept of ATM is dependent on the implementation of the network control mechanism. Unlike shared medium, such as fiber distributed data interface (FDDI) or ethernet, the aggregate bandwidth of an ATM network



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Ramp
cell loss
cell_loss_mode_on
XYMg
VEM cell /s1/yu/ptolemy/src/atm/cell_loss:schematic
fork
Binom
Binom
Add
Gain
Add
TWM Icon Manager
/s1/yu/ptolemy/src/atm
/s1/yu/ptolemy/src/atm
init.pal:schematic
suzette
xgraph
Close
Hardcopy
ATM_Cell_Loss
ATM_cell_loss_prob
detection_mode_off
detection_mode_on
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1e-04
3
1e-03
3
1e-02
3
1e-01
bit_error prob
Manual Browser
Help
Quit
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increases as nodes are added. The dynamic bandwidth characteristic is achieved by statistical multiplexing [7].

Consider a bank of n variable bit rate sources that enter an ATM network, and are sent to n different destinations. As more variable bit rate sources are added to the network, the total transmission rate exhibits less aggregate burstiness, assuming statistically independent sources. As the number of sources increases, the variance of the total bit rate approaches zero. Thus, statistical multiplexing will enable a higher network utilization than existing circuit switching networks. It should be noted that for a point-to-point communication system, such as an RF link, there does not exist any statistical multiplexing. Any multiplexing of data or sources occurs at either the source point, and/or the destination point.

The ATM protocol defines an Adaptation Layer (AAL), which enables ATM to provide for different types of communication services. The AAL is responsible for segmentation of source data into ATM cells, and reassembly at the destination. The classes of services are intended to match the characteristics of varying types of data. For example, compressed video data is typically a variable bit-rate, and real-time process, while local area networks are characterized by short, highly bursty transfers. Although the Adaptation Layers being defined by the ATM Forum are still evolving, in general there are four main types:

Type 1: Constant Bit Rate Service
Type 2: Variable Bit-Rate Service
Type 3: Connection-Oriented Variable Bit Rate Data Transfer
Type 4: Connectionless Variable Bit Rate Data Transfer

As previously described, an ATM cell is defined as 5 bytes of header information, and 48 bytes of data payload. Depending on the AAL type, however, not all 48 bytes of the data payload are user information. Up to 4 bytes of the data field may be used by the adaptation process. For connectionless type of service, all 48 bytes are available for user data. In this case, the ATM protocol overhead is approximately 10% (5 bytes out of 53 bytes).

The AAL process is divided into two sublayers: the convergence sublayer (CS) and the segmentation and reassembly sublayer (SAR) [8]. The output of each sublayer is called a protocol data unit (PDU). The PDU for the CS sublayer is variable length, dependent on the type of AAL. The PDU for the SAR sublayer is a fixed length of 48 bytes to fit into the payload field of an ATM cell (See Appendix B).

VI. Frame Efficiency

Units of user information (called frames in this discussion) are passed to the AAL layer. The CS part of the AAL adds appropriate header and trailer to the frame, which is needed to support the segmentation process. The resulting CS-PDU is split by the SAR into fixed size segments that fit into an ATM cell payload. Depending on the type of AAL layer, the SAR may add its own Protocol Information. In the case of AAL type 4, information for the receiver to reconstruct the frame is attached. The resulting SAR-PDU is passed to the ATM layer to transport as an ATM cell.

A standard method to control errors is automatic repeat request (ARQ). A common form of this error control method is selective-repeat ARQ. One implementation of selective-repeat ARQ provides that each frame the source sends is either acknowledged (ACK) or not acknowledged (NACK) by the destination. If the source receives a NAK, the source must retransmit the corresponding frame. Frames may not reach the destination in the case of channel bit-errors. Let M be a random variable equal to the total number of transmissions for each frame. M is a geometric random variable, with p being the probability of a frame requiring re-transmission.

$$P[M = k] = (1 - p)\, p^{k-1}$$

The average number of transmissions is the expected value of M:

$$E[M] = \sum_{k=1}^{\infty} k (1 - p)\, p^{k-1}$$

Noting that:

$$\sum_{k=1}^{\infty} x^k = \frac{1}{1 - x} \quad (\text{for } x < 1)$$

and differentiating:

$$\sum_{k=1}^{\infty} k\, x^{k-1} = \frac{1}{(1 - x)^2} \quad \text{(i)}$$

Using (i)

$$E[M] = (1-p)\frac{1}{(1-p)^2} = \frac{1}{1-p}$$

A frame is retransmitted if any of the cells in the frame have been corrupted. For each frame, there is a fixed amount of overhead (CS sublayer adds header and trailer to the frame). The larger the size of the frame, the smaller the overhead ratio. However, the probability of frame retransmission is greater, since there is an increased chance of at least one cell being corrupted.

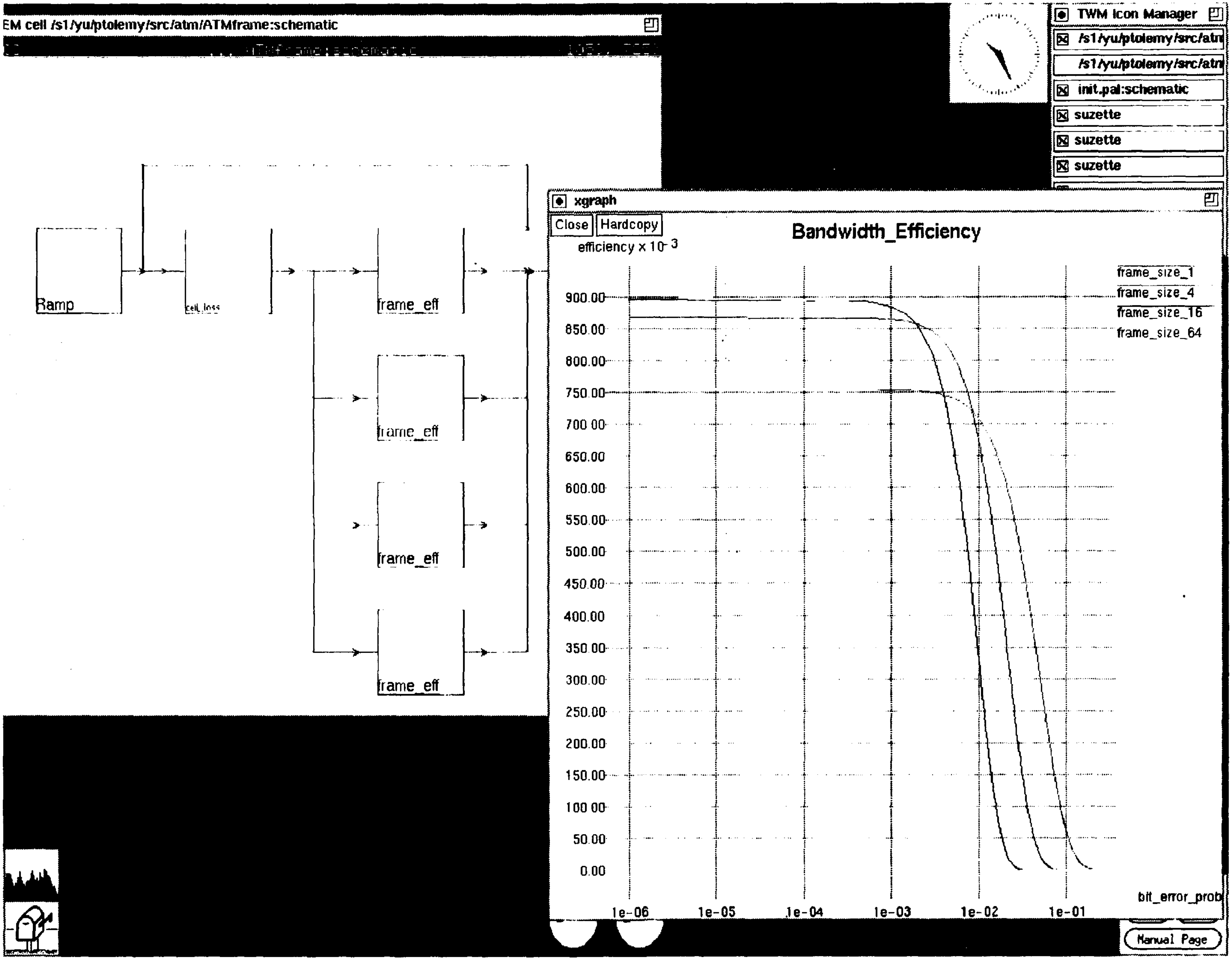
Assume 8 bytes of overhead for each frame. The bandwidth efficiency is determined by the ratio of bytes that are user data, to the total number of bytes transmitted. For example, consider a frame size of four ATM cells. The total number of bytes transmitted is 53 bytes per cell, and in this case (53 x 4) bytes. Assuming all 48 bytes of the ATM payload is user data, the total number of bytes of user data is (3 x 48) + (48 - 8), accounting for the 8 bytes of overhead for the frame. In general, tne bandwidth efficiency for a frame length of n is,

$$\text{bandwidth efficiency for frame of size } n = \frac{48(n-1) + (48-8)}{53n}$$

We note, in the limit as $n \rightarrow \infty$, the bandwidth efficiency is monitonically increasing towards 48/53. Channel bit-errors may corrupt ATM cells, which will require retransmission of the corresponding frame. For each retransmission, the entire frame is redundant information. The bandwidth efficiency, with the average number of retransmissions being E [M], is therefore,

$$\text{bandwidth efficiency with retransmission} = \frac{48n-8}{53 * E[M]}$$

Bandwidth efficiency for frame sizes of 1, 4, 16, and 64 are plotted in figure 4. For a low probability of bit-error, the greater the frame size, a higher bandwidth efficiency is experienced. However, as the probability of bit-error increases, the penalty of re-transmitting the frame overcomes this gain.



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TWM Icon Manager
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init.pal:schematic
suzette
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Ramp
cell_loss
frame_eff
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Manual Page

VII. Frame Loss and Burst Errors

In the analysis thus far, bit-errors have been assumed to be a Bernoulli process; that is, the probability of error for each bit is an independent event. Many times, however, channel-bit errors occur in bursts. The duration of the burst errors, and the size of the frame, will have an effect on the transmission performance. To study the effect of burst errors and the relationship with the size of the frame, we consider burst errors of cells, and not bits. Therefore, a burst error of length 4, will cause 4 consecutive cells to be corrupted.

Assume burst errors occur for length k. To provide a comparison of the effect of the length of the burst errors, the expected overall cell error should be held constant. Define a Bernoulli process, X_i, where a "success" denotes a burst error of length k beginning at cell position i. A "failure" represents a single valid cell at cell position i. We have:

$$P(X_i = 1) = p_k$$
$$P(X_i = 0) = 1 - p_k$$

Define the random process Y_i, as a function of X_i

$$Y_i = \begin{cases} 1 \text{ if } X_i = 0 \\ k \text{ if } X_i = 1 \end{cases}$$

Y_i can be rewritten as:

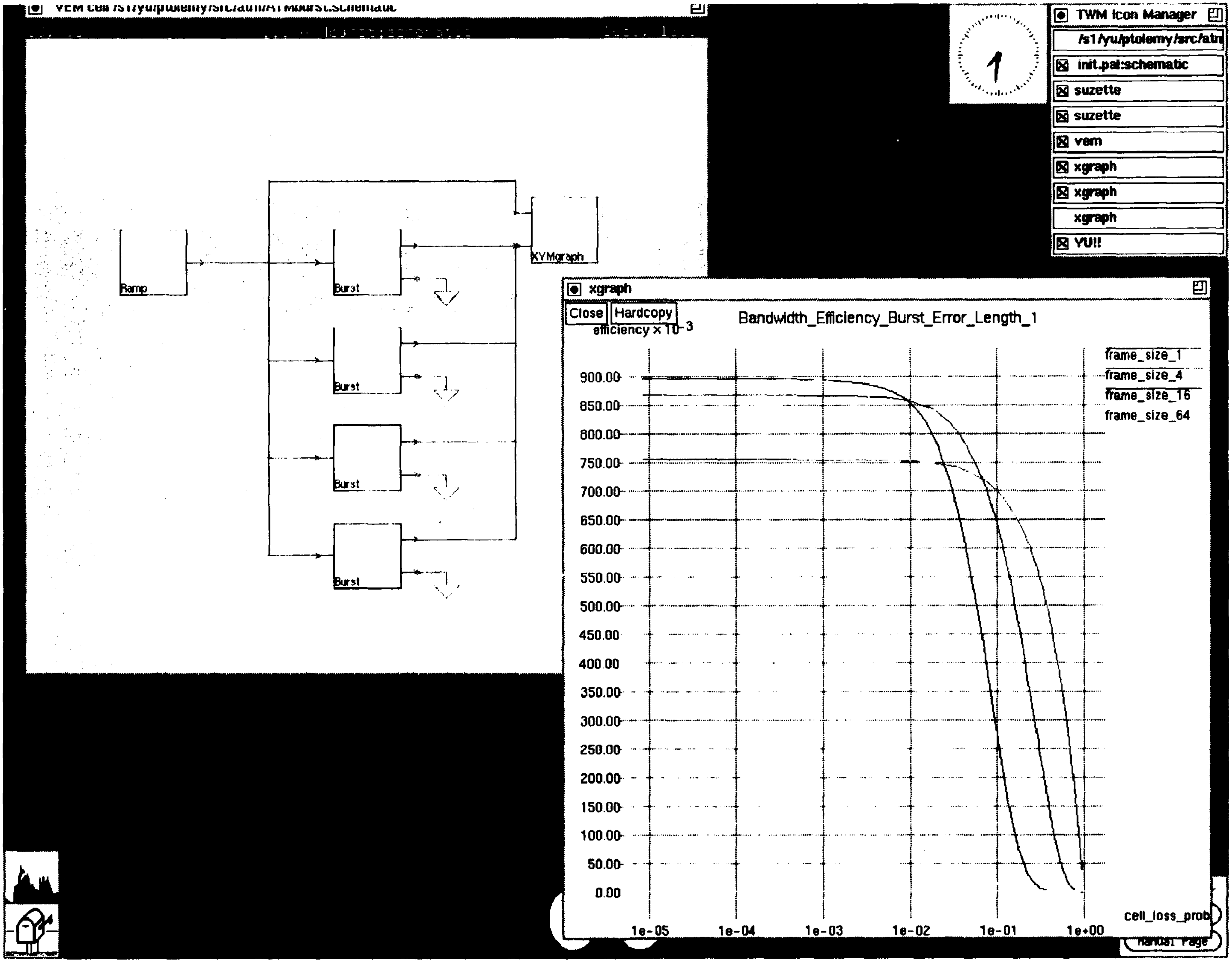
$$Y_i = (k - 1) X_i + 1$$

The expression, $\sum_{i=1}^{N} Y_i$, represents the total number of cells where N is the number of trials. The expected value is:

$$E[\sum_{i=1}^{N} Y_i] = N\{(k-1) E[X_i] + 1\}$$
$$= N(k-1) p_k + N$$

The aggregate number of cell errors is:

$$N(k-1) p_k + N p_k$$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150.00
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50.00
0.00
1e-05
1e-04
1e-03
1e-02
1e-01
1e+00
cell_loss_prob

To keep the overall cell loss equivalent for different burst lengths, we have:

$$p_1 = \frac{N\,(k-1)\,p_k + N\,p_k}{N\,(k-1)\,p_k + N}$$

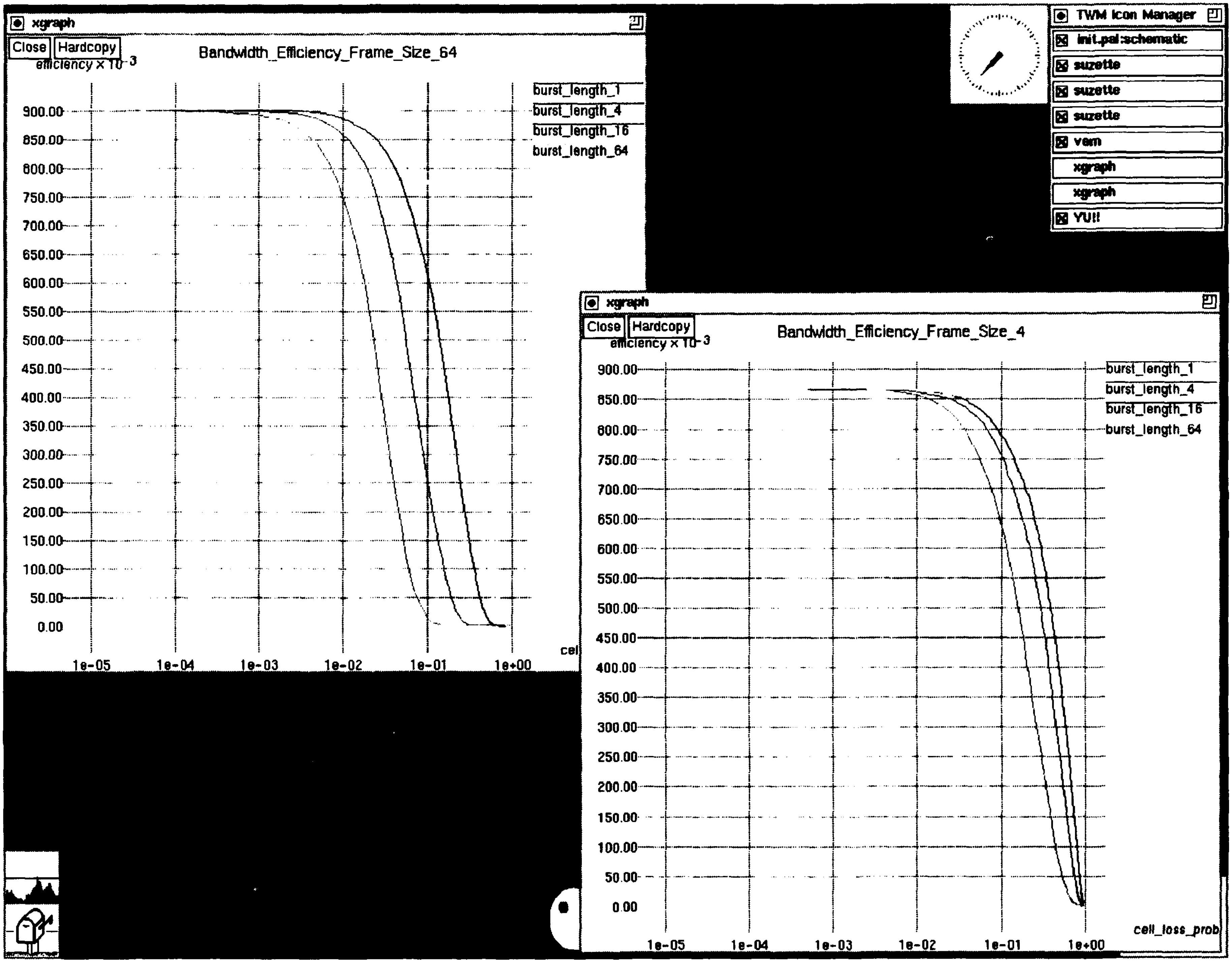
Rearranging, we have:

$$p_k = \frac{p_1}{k\,(1-p_1) + p_1}$$

With p_k defined, burst cell errors of length k can be generated so that the overall cell loss remains a constant for varying values of k. First, a simulation with a burst error of length 1 for different frame sizes is plotted in figure 5. Note that a burst error of length 1 degenerates into the case of random cell errors. As expected, the plot is precisely that of figure (xx), with the appropriate scaling of the x-axis.

Now consider fixing the frame size to 64, and vary the burst error length. Simulation results are given in figure 6. For this case, we recognize that the bandwidth efficiency improves as the burst error length increases. What we are observing is that for a given frame size of 64, the ratio of frames corrupted decreases for a longer burst error length. For example, for a burst error of length 1, an error can occur in any of the 64 cells to cause a frame loss. On the other hand, for a burst error of length 64, if the burst coincides exactly with a frame, 64 cells are corrupted but only one frame is required for retransmission. It should also be noted that for frame size of 1, the *overall* frame loss probability is always p_1, for any length of burst errors.

Lastly, we consider a frame size of 4, and plot the results for burst errors of length 1, 4, 16, and 64 (see figure 6). Here we notice that the bandwidth efficiency improves for a burst error of length 4, in comparison to a burst error of length 1, and again improves for a burst error of length 16 in comparison to frame size 4. However, the bandwidth efficiency is nearly equal for a burst error of length 64. In this case, the decrease in the inter-frame corruption for a given burst, is offset by the randomness of the errors.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cell_loss_prob

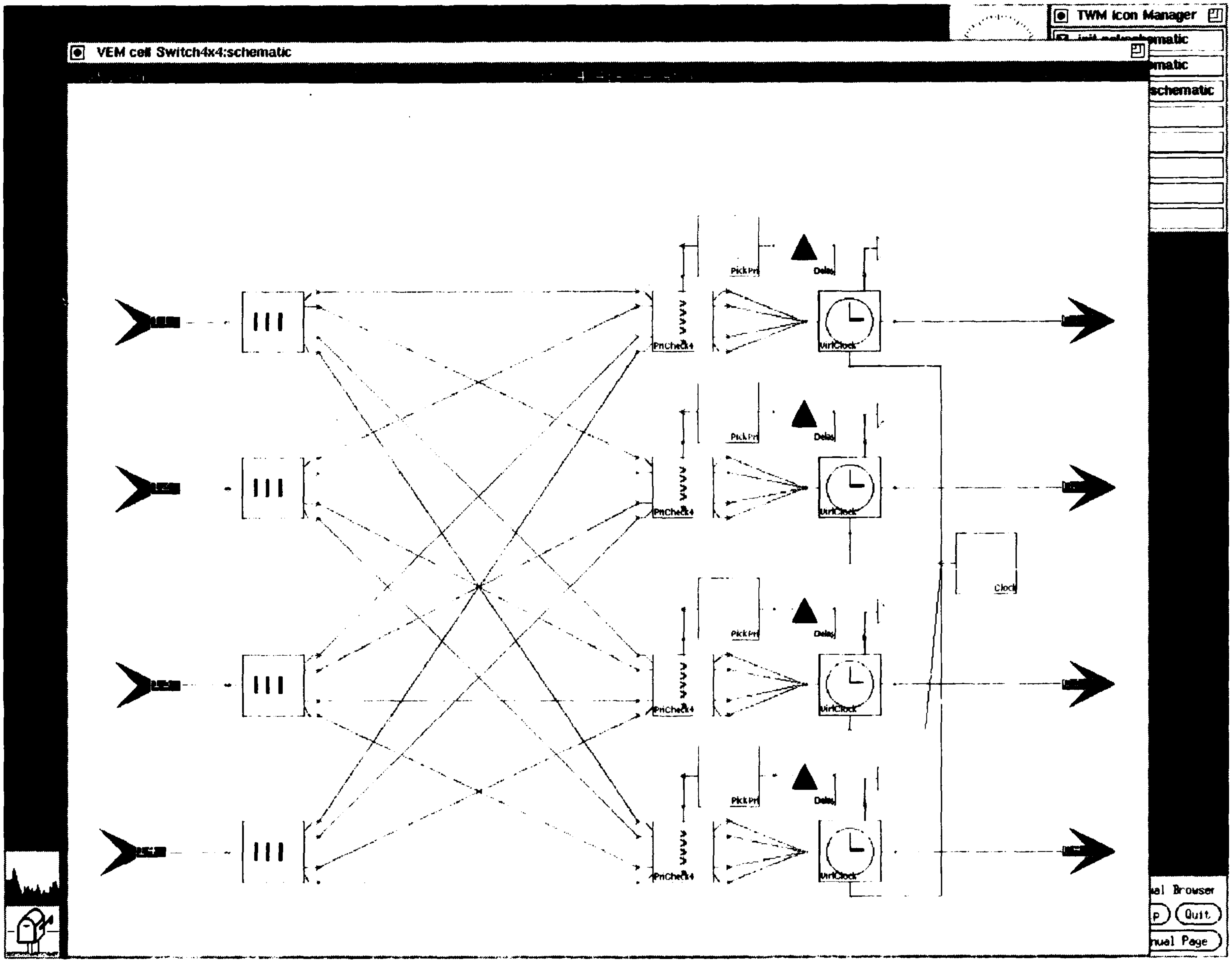
VIII. Graphical Design Environment

The simulations and analytical computations in this report have been done with a software package, Ptolemy, which is distributed by the University of California at Berkeley as public domain software [9]. Commercially introduced graphics-based design systems have accelerated in the past several years. With the pervasiveness of workstations, the power of graphics is being exploited. (Ptolemy can be obtained via anonymous ftp (file transfer protocol) at "ptolemy.berkeley.edu")

Ptolemy provides the standard icon-based graphical programming environment that is omnipresent in today's software packages. Hierarchical representation capability is also provided, and an example of this can be seen in figure 3. The window in the left bottom corner represents "cell_loss", which is a block in the window in the upper left corner of the screen. Ptolemy allows an unlimited depth in hierarchy. The basic building blocks are encapsulated C++ code. For example, referring again to figure 3, the block "Binom" in the lower left corner window is C++ code that executes a binomial expansion. Ptolemy is a C++ developed software application which allows the features of object oriented programming to be exploited.

Signal Processing Worksystem (SPW) by Comdisco, and OPNET are just two examples of a wide array of commercial software packages that have been released in the past several years that have certain similarities with Ptolemy. Commercial packages have the advantage over university products in providing software support and services. In addition, commercial products will generally adhere to and follow more closely the evolving industry standards. A distinction of Ptolemy, however, is the underlying philosophy of an environment for the simulation and prototyping of *heterogeneous* systems. The simulation model for nearly all commercial DSP packages are horizontal in nature (i.e. a specific processor, code generation, VHDL, network simulation) Ptolemy enables the overall simulation to be arbitrarily heterogeneous; a cluster executed on a processor, a cluster simulated as software, executing in unison. It should be noted that several commercial companies are beginning to introduce elements of heterogeneous simulation into their software packages.

A basic abstraction in Ptolemy is the "Domain", which specifies a computational model that defines a particular type of subsystem [10]. Existing "domains" that have been developed include synchronous and dynamic dataflow, discrete-event, and C-code generation. A domain can also specify a particular hardware system. Ptolemy enables these domains to be mixed, as appropriate, to realize an overall system simulation.



VEM cell Switch4x4:schematic
TWM Icon Manager
schematic
PickPri
Delay
PriCheck4
VirtClock
Clock
Quit

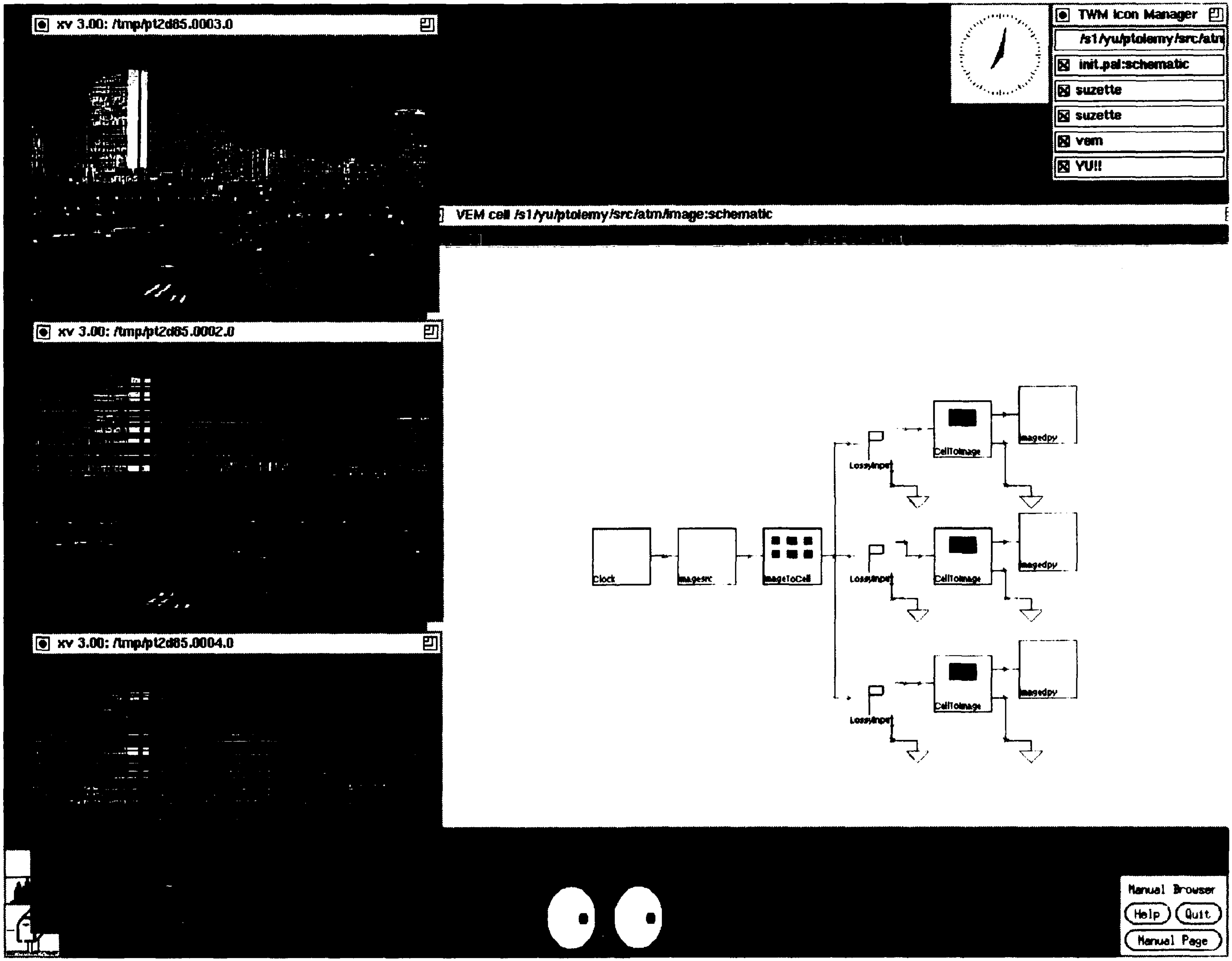
As simulation modeling of ATM networks become more complex, a software package such as Ptolemy is needed; a *framework* that enables segments of a simulation to be completed at the appropriate abstraction level. Some work in the area of ATM switch modeling has been completed by U.C. Berkeley. Paul Haskell and Greg Walter of U.C. Berkeley have completed a 4x4 ATM switch simulation in Ptolemy (see figure 7). Another example is a simulation of image transmission over ATM networks (see figure 8).

IX. Conclusion

Some preliminary analysis of the performance of the ATM protocol over microwave channels has been completed. Analysis of the effect of the detection mode in operation for high bit-errors is presented. The performance of frame size, and the effect of burst errors is also outlined. In each case, for low bit-errors, which is the characterization of optical fiber transmission, no appreciable performance degradation is observed. As the probability of bit-error increases, a distinct transition period is seen, where the performance dramatically degrades.

As the effort in "pushing" the ATM protocol "off the fiber", an understanding of the merits of ATM is necessary. In commercial application, the accelerated activity in the ATM community is a result, in many respects, of the fact that ATM is being developed with SONET, which is based on optical fiber transmission. In some applications, a given amount of overhead incurred is not a problem, provided a required data rate is achieved. In other applications, bandwidth *efficiency* may be more important.

Certainly there are distinct advantages in maintaining the ATM protocol over RF. These advantages include maintaining a common protocol. As communication and computer networks continue to merge, and multi-media continues to evolve, a common protocol will be advantageous. Also, by extending the ATM network over RF, bridging two optical fiber networks will be accomplished. There are, however, numerous challenges. It is anticipated that through a combination of experimentation and simulation/modeling, a better understanding of these questions, and a determination of the relevant issues will become evident.


xv 3.00: /tmp/pt2d85.0003.0
xv 3.00: /tmp/pt2d85.0002.0
xv 3.00: /tmp/pt2d85.0004.0
TWM Icon Manager
/s1/yu/ptolemy/src/atn
init.pal:schematic
suzette
suzette
vem
YU!!
VEM cell /s1/yu/ptolemy/src/atm/image:schematic
Clock
Imagesrc
ImageToCell
LossyInput
CellToImage
Imagedpy
Manual Browser
Help
Quit
Manual Page

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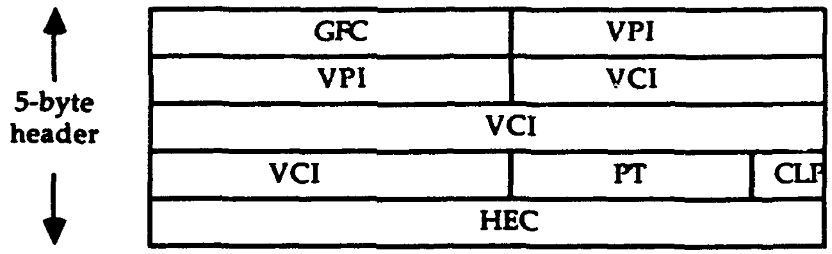
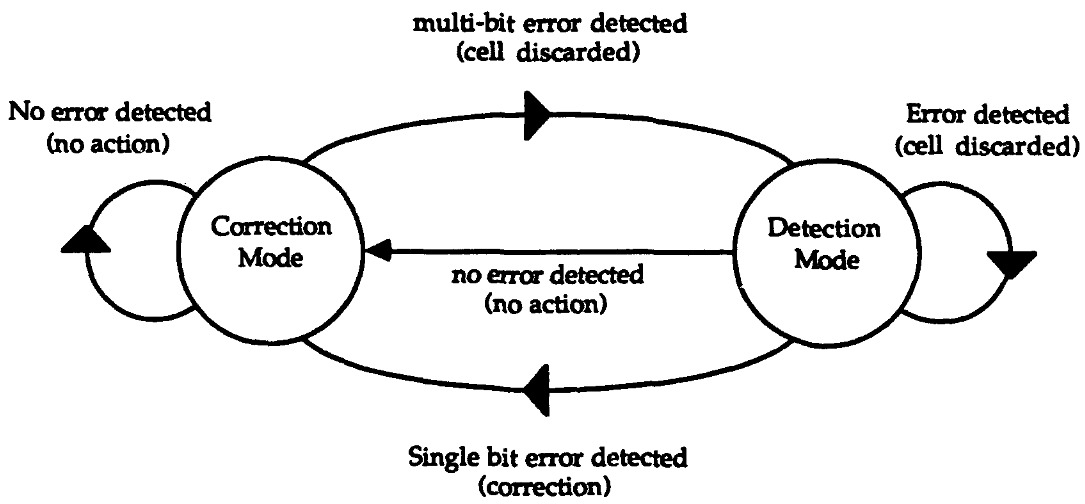


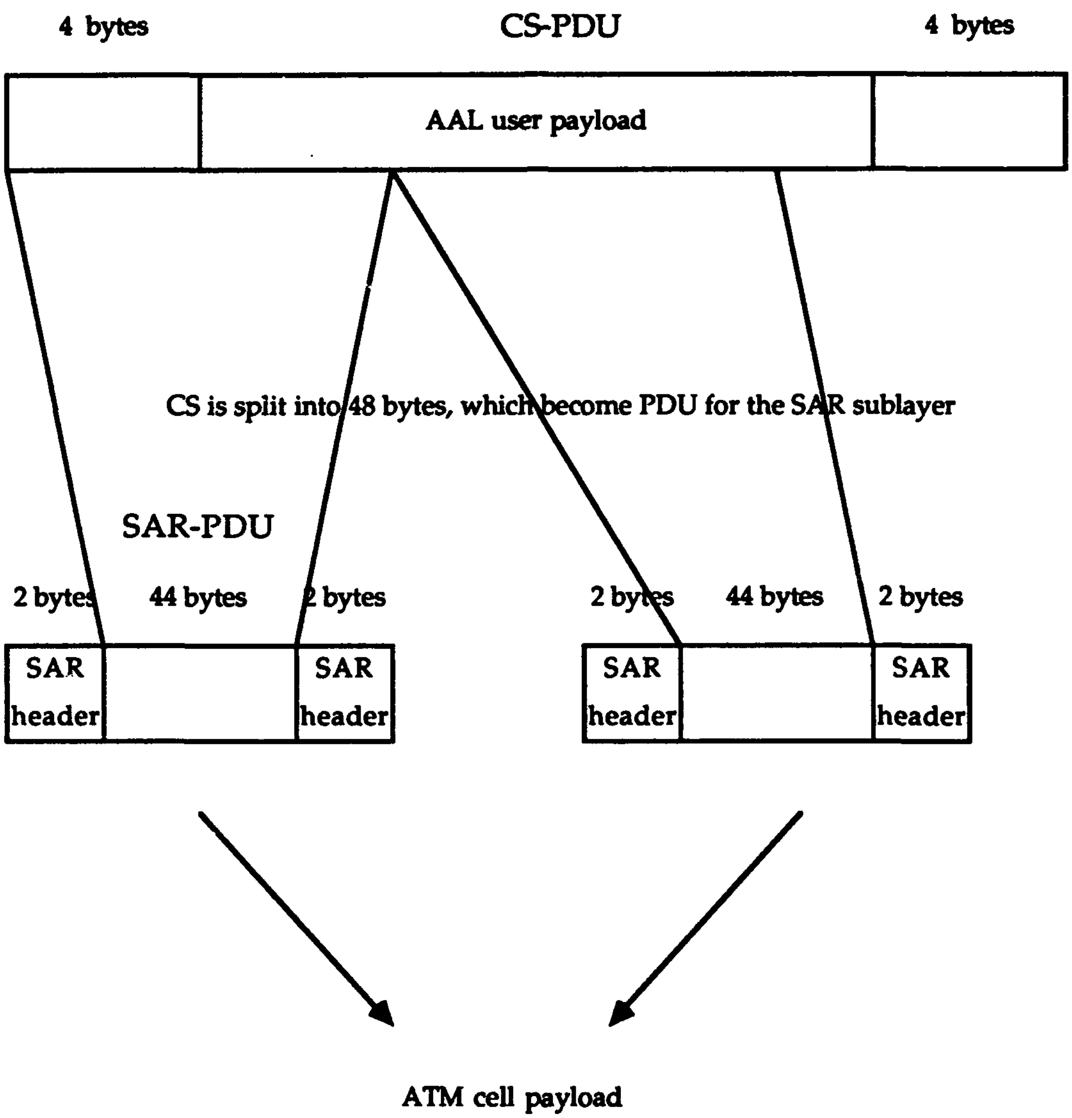
Appendix A.1

(ATM Cell Header Format)



Appendix A.2

(Detection/Correction Mode State-Diagram)


4 bytes
CS-PDU
4 bytes
AAL user payload
CS is split into 48 bytes, which become PDU for the SAR sublayer
SAR-PDU
2 bytes
44 bytes
2 bytes
2 bytes
44 bytes
2 bytes
SAR header
SAR header
SAR header
SAR header
ATM cell payload

Appendix B